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Planar Laser Induced Fluorescence System for High Pressure Combustion Facility

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13. ABSTRACT (Maximum 200 words)

This report covers the expenditure of DURIP grant for the design, fabrication and assembly of a state-of-the-art planar laser-induced fluorescent (PLIF) instrumentation system. The equipment will be used to acquire time-accurate and spatially resolved species concentrations of OH and NO in a combustor test rig operating at flow rates as high as 1 kgm/s and up to four atmospheres. Successful initial results have been obtained for methane-air flames at atmospheric pressure. This apparatus forms a significant addition to the Caltech program of research in combustion instabilities and applications of active control to combustor dynamics.

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1 Research Objectives

The funds supporting the work reported here were provided by a DURIP grant. This report covers the design, fabrication and assembly of a state-of-the-art planar laser-induced fluorescence (PLIF) instrumentation system. The equipment will be used to acquire qualitative and quantitative, time-accurate and spatially resolved species concentrations of OH and NO. Results for the first, OH, should resolve flame zones; results for NO will be used to monitor the production of pollutants in time-varying combustion zones. The system has been assembled and operated successfully for frequencies of time-dependent combustion up to 22 Hz. We anticipate that operation to 100 Hz should be possible with the existing apparatus.

Eventually the system will be used with a high pressure, high flow rate combustor test rig currently being assembled. The PLIF system is being used nearly routinely for investigation of methane/air flames at atmospheric pressure. A flames is produced in the region above an eductor in which initially unmixed methane in a central jet is entrained by a coaxial flow of air-Time-dependence is imposed by shining planar acoustic waves on flame located near the base of a large quartz tube. The acoustic waves are generated by two loudspeakers mounted in perpendicular branches at the top of the tube. This apparatus has proven to provide an excellent opportunity for learning the operation of the PLIF system and for developing the necessary software for data acquisition and processing.

2 Introduction

The combustion process for a propulsion system or stationary power plant can take place over a wide range of pressure and temperature conditions, however, a number of important characteristics remain constant. Whether propellants are supplied in gas, liquid, or solid phases, effects of geometry, mixing, and non-uniform properties can cause the flowfield to be intrinsically unsteady. Processes which are unstable on small scales spread to macroscopic levels, until they are identifiable as fluctuations of global properties, notably the combustion chamber pressure. These unsteady pressure oscillations are generically known as combustion instabilities. The pressure excursions associated with these instabilities can cause unacceptable levels of vibration, and also enhance heat transfer rates significantly enough to cause structural damage. In addition, the impact of combustion instabilities in association with pollutant emissions has become increasingly important due to government regulations on emission levels.

Premixing of fuel and air is now recognized as one of the most promising, if not the preeminent technique to lower NO_x emissions in gas turbine combustors. In addition, operation as close as possible to the lean blowout limit is desirable to minimize high flame temperatures, which also contribute to the production of NO_x. These circumstances give rise to favorable conditions under which combustion instabilities are more likely to occur, and have in fact occurred in new combustors incorporating these principles. The planar laser-induced fluorescence (PLIF) instrumentation system proposed in this document will contribute substantially

to the understanding of the fundamental processes involved in both pollutant production and combustion instabilities. These results will be applied to active control strategies to minimize both processes, as well as to determine the dominant mechanisms affected by control.

A high pressure combustor flow rig, unique to a university research facility, will eventually form the primary location studies involving the PLIF system. The laboratory combustor can operate with mass flowrates of 1.1 kg/sec at pressures of 4 atm, as well as span a wide range of conditions below this operating point. Initial studies are planned for a 2-D combustor burning premixed methane and air, with a wedge-shaped flame stabilizer. The combustor is designed to be interchangeable, such that a wide variety of combustor geometries can readily be studied, as well as both liquid and gaseous fuels. A wide range of diagnostic tools are presently available for use with this facility; however, none are capable of resolving the concentrations of species such as NO and OH inside the combustor.

The PLIF system is capable of resolving the species previously mentioned in a spatially and temporally accurate fashion. Useful lifetime of the instrumentation system is estimated to be approximately 10 years, which is also the estimated life of the combustor facility. This is due primarily to recent advances in laser and ICCD camera technology, which provide purer laser beam quality, faster repetition rates, improved camera sensitivity, and higher spatial imaging resolution. Other applications of the PLIF system include imaging of the temperature field, velocity fields (with additional equipment), and species measurements of virtually any other species of interest, due to the tunable nature of the dye laser.

Experiments involving fluctuations in mixing ratios and combustion instabilities will be carried out in the combustor. Local OH levels will reveal reaction zones and burning rates, while NO concentrations will pinpoint regions of pollutant production. This will aid in the identification and classification of fundamental processes which contribute to pollution generation and the onset of combustion instabilities, as well as characterizing the effects of unmixedness. This information at a microscopic level will be invaluable in developing better control strategies, as well as refining analytic and computational models currently being studied.

The addition of a PLIF instrumentation system integrates well with current research at Caltech, as well as with research interests of DOD. This program of research pertains to BAA 97-1 of the Air Force Office of Scientific Research, in the Space Power and Propulsion section (Dr. Mitat A. Birkan), which is supporting research to predict and suppress combustion instabilities in liquid rocket systems; Dr. Birkan currenlty supports work in this area at Caltech under AFOSR Grant No. F49620-96-1-0149. The work also applies to the Airbreathing Combustion section of AFOSR (Dr. Julian M. Tishkoff), in which a need to develop a more fundamental understanding of turbulent reacting flows is expressed. The Propulsion program (Dr. Gabriel D. Roy) of the Office of Naval Research will also find aspects for improving combustion performance and reducing pollutant emissions of relevance to their research goals. Current sources of program funding in our

laboratory include Caltech, ENEL (Italian Power company), AFOSR; and DOE Advanced Gas Turbine Systems Research (AGTSR) program.

Gas turbine research has progressed to the point in which a more detailed understanding of the combustion process is necessary to meet current demands. The environmental impact of pollutant emissions such as NO, improving efficiency, suppressing combustion instabilities, and applications for passive and active control techniques in combustion systems are all important research concerns. Quantitative information regarding precisely where NO is formed in the combustion chamber under various conditions, such as oscillations experienced during combustion instabilities and when the system is actively controlled, would be extremely useful in combustor design. This information, used in conjunction with OH levels, an intermediate species in combustion which characterizes flame zones and burning rates, can aid in the development of stable, low NO_x gas turbine systems.

In order to achieve this goal optimally, it is evident that some form of control must be exercised on the combustor, possibly in the form of actuation of the primary or secondary fuel supply (Schadow et al., 1996). Current active control methodologies for combustion instabilities have met with limited success; however, the reasons for these successes are mere speculation. There are virtually no detailed measurements which clarify the dominant mechanisms involved when active control is applied to the combustor. There is a strong need to resolve these issues in order for active control strategies to be applied rationally and to aid development of scaling laws, which are major focuses of the proposed PLIF measurement.

3 Combustor Test Rig

Progress continues to be made on a combustor test rig. Business troubles at Alturdyne, Inc. (the principal contractor for the rig) have slowed production of the unit and made the delivery date uncertain. We are currently working with Alturdyne in an attempt to resolve the situation.

A schematic drawing is shown in Figure 1 is a line drawing of the main components. Compressed air is supplied as the oxidizer by a 230 horsepower gas turbine engine load compressor. This compressor is capable of delivering up to 2.5 pounds of air per second, at pressures up to 4 atmospheres.

In the systems principal configuration, fuel is provided from a methane bottle tank farm. This fuel is controlled using a series of redundant solenoid valves and a double reduction regulator scheme. However, it is possible later to adapt the rig for use with liquid fuels.

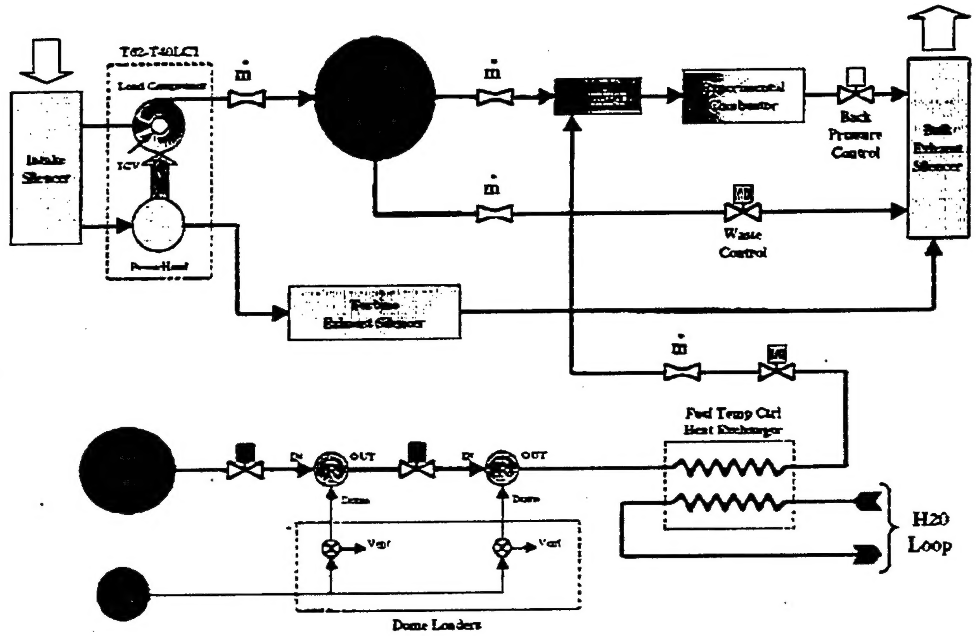


Figure 1. Basic Schematic of Combustor Test Rig

Currently, all large components for the unit have been fabricated and the turbine/compressor assembly as well as its controls has been tested on several occasions. Two of these tests were used to verify the effectiveness of the silencing equipment. It was found that the inlet and exhaust silencers reduced the broadband noise by 40 dB from ~130 dB to ~90 dB at ten feet. A picture of the rig, partially assembled is shown in Figure 3.

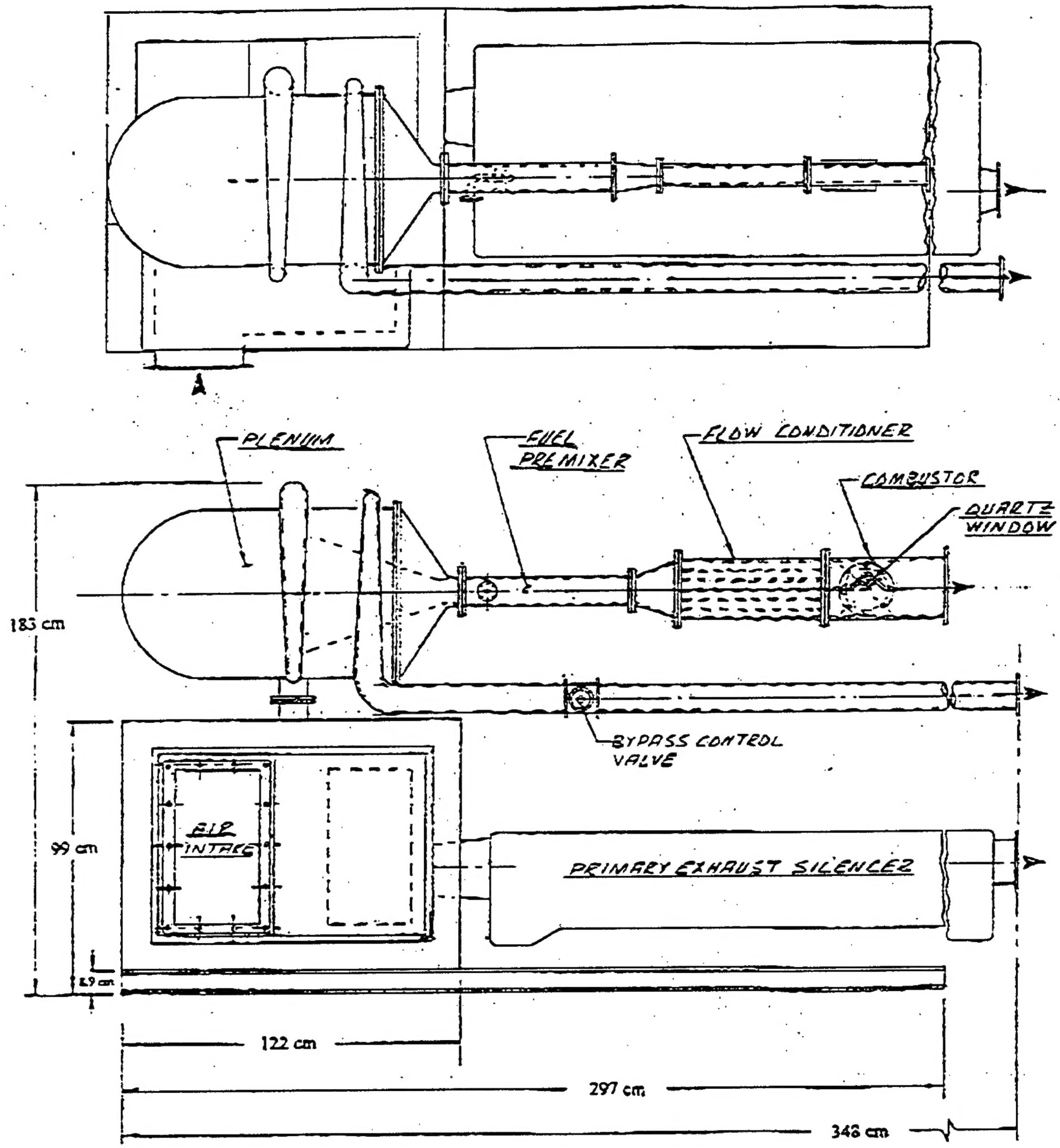


Figure 2. Combustor Flow Rig Overview

To date, the following rig and ancillary components have been fabricated:

1) Main system support frame
2) Load compressor subframe and mounts
3) Load compressor fuel system
4) Load compressor oil cooler system
5) Load compressor sound attenuating enclosure
6) Primary inlet silencer
7) Secondary inlet silencer
8) Primary exhaust silencer
9) Secondary exhaust silencer and subframe
10) Load compressor discharge plenum
11) Load compressor control system
12) Experimental combustor coolant reservoir, coolant pump and subframe
13) 275 gallon load compressor fuel tank
14) Overhead bridge crane for rig maintenance
15) Ancillary component control panel

The following components are either under construction or waiting to be fabricated:

1) Compressor to plenum plumbing
2) Plenum to secondary exhaust silencer bypass leg plumbing
3) Combustor leg flow meter and slip joint
4) Back pressure control valve
5) Exhaust cooling system (water injection)
6) Fuel premixer
7) Experimental combustor
8) Experimental combustor fuel feed system and controls
9) Tank farm bottle rack

The basic design of the unit was constrained by the following requirements:

1) The system should provide air to the experimental combustor at flow rates and pressures that are comparable to those seen at the lower range of practical gas turbine combustors, while maintaining low enough pressures so that line broadening does not become a problem with PLIF diagnostics.

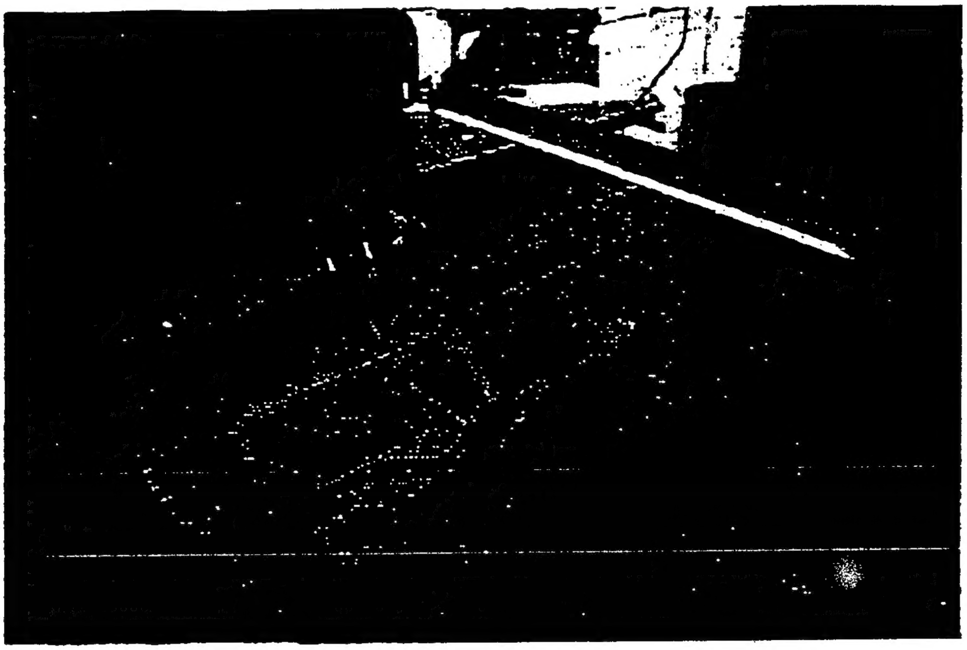


Figure 3. Combustor rig partially assembled

2) The air supply should be a continuous duty source. This allows for variations in test conditions while the combustor is operating and also provides the necessary test time required for studies in active control of combustion instabilities.

3) The combustor track should be versatile, providing easy access and the ability to quickly change premixer and combustor components.

4) The unit should be relatively quiet in order to meet the necessary sound level requirements established by the GALCIT community.

5) The unit should meet the necessary safety requirements as are appropriate to an academic environment.

Nominal Discharge	1.13 kg/s at 4 atm
Rotor Speed	64,643 RPM
Compressor Mass	125 kg
Fuel Type	JP-4, JP-5, or Diesel
Fuel Consumption	53 kg/hr no load, 110 kg/hr full load

Table 1. Compressor Characteristics

The resulting design incorporates a Turbomach Titan T62T40-LC-1 gas turbine powered load compressor as an air source. At its design point, this high speed compressor is capable of delivering 2.5 lbs of air per second at four atmospheres. In the combustor test rig, this air is discharged directly in a plenum, which decouples the compressor from downstream disturbances. From here, some of the air is bypassed through a control valve and dumped directly into a secondary exhaust silencer. The remaining air from the plenum

flows into the experimental combustor track. This pathway varies depending on the configuration of the system, but in general consists of a premixer and combustor. After leaving the combustor, the flow passes through a backpressure control valve and then is also dumped in the secondary exhaust silencer. By varying the settings of the two control valves as well as the inlet guide vanes on the compressor, it is possible to sweep a wide range of combustor pressures and flow rates.

4 The PLIF System

The PLIF system assembled at Caltech is based on a Continuum Powerlite 9010 Nd:YAG laser, pumping a Continuum ND6000 dye laser, which in turn drives a Uniwave mixer/doubler system (Figure). Use of Rhodamine 590 dye in the ND6000 to optimize conversion efficiency at 566 nm, gave pulses in excess of 200 mJ. Frequency doubling this beam to hit an OH line at approximately 283 nm yielded greater than 60 mJ/pulse at full power. Since conversion efficiency is so high, it is not necessary to operate the Nd:YAG laser at full power. The high efficiencies of the laser system will be required in later tests, when less abundant species such as NO are probed.

The second major component in the PLIF system is the detector. It consists of a Princeton Instruments ICCD-MAX intensified CCD camera, using a Thomson 512x512 CCD array, and a DEP intensifier. Attached to the camera is a catadioptric UV lens, with a focal length of 105mm and f/# of 1.2. This lens is ideal for this application because of its low f/#, all quartz construction for UV transmission, and lack of spherical aberration due to the catadioptric design. A minor drawback is the need to purge the detector with dry nitrogen, since the addition of the lens to the camera unseals the system. The fluorescence signal the detector measures is filtered by 2mm thick UG5 and WG305 Schott glass filters. A Stanford Research Systems DG-535 digital delay/pulse generator controlled camera timing, which is synchronized to the laser pulse.

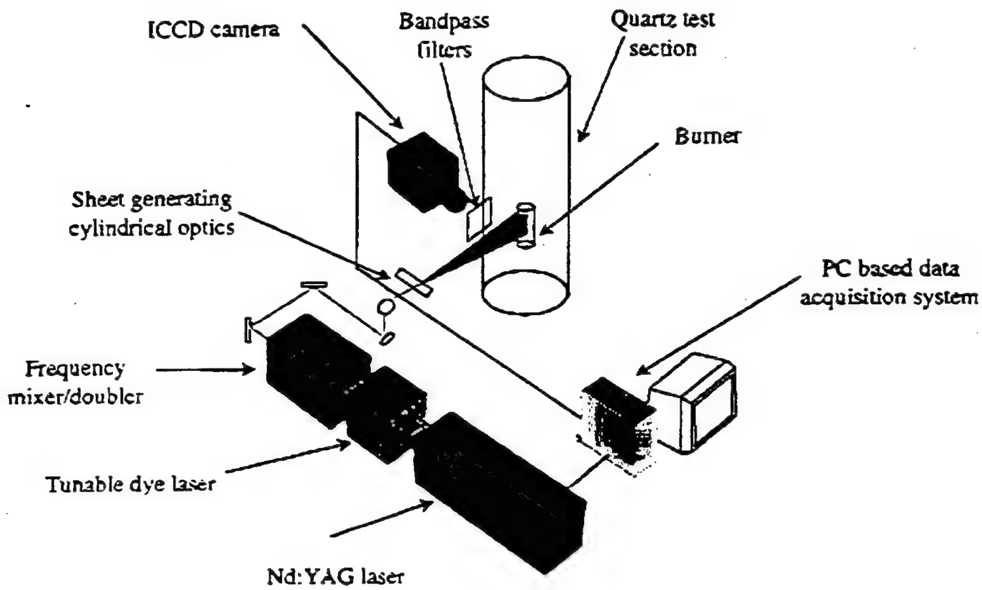


Figure 3. PLIF System Schematic

The spatial resolution of the ICCD camera with the catadioptric lens is approximately 215μm x 215μm per pixel. It is limited by the size of the CCD array (512 x 512) and the image size when the lens is focused. To obtain high temporal resolutions, a periodic phenomenon with high reproducibility is required while phase-locking. Higher temporal resolutions require more data points to fill in the "gaps" in the curve (see Figure). In this case, the acoustic driving frequency was 22 Hz, and sampling was done at 3703 Hz. It is anticipated that frequencies on the order of 1 kHz can be resolved with the current system.

Additional instrumentation includes several type K thermocouples, a PCB 106B50 ICP pressure sensor and a PCB 428-A16 signal conditioner. The pressure transducer has a sensitivity of 493.3. mV/psi and a low frequency response of 0.5 Hz. The data acquisition boards used were Computer Boards CIO-DAS1602/16, CIO-DAS1602/12, and an EXP-16, each installed in an AMD Athlon 650 MHz PC running LabView.

5 Initial Test Results

The immediate purpose of the work described in this report is to use the new PLIF system for studying the flame dynamics of various burner configurations, and their interaction with chamber acoustics. A burner is sought which has a reduced sensitivity to a forced acoustic field. It also serves as an opportunity to demonstrate the proof of concept and gain experience with laser diagnostic techniques. The work carried out here can readily be extended towards longer term goals of obtaining spatial and temporal resolutions of various species in addition to OH, such as NO and CH. This will guide combustor designs and active control efforts that minimize sensitivities to chamber acoustics, suppressing the onset of combustion instabilities, and also contributing to an improved reduction in emissions of harmful NO_x pollutants.

5.1 Test Apparatus

The test section consists of three major components: the burner, the acoustic cavity, and the acoustic driving system shown schematically in Figure 4.

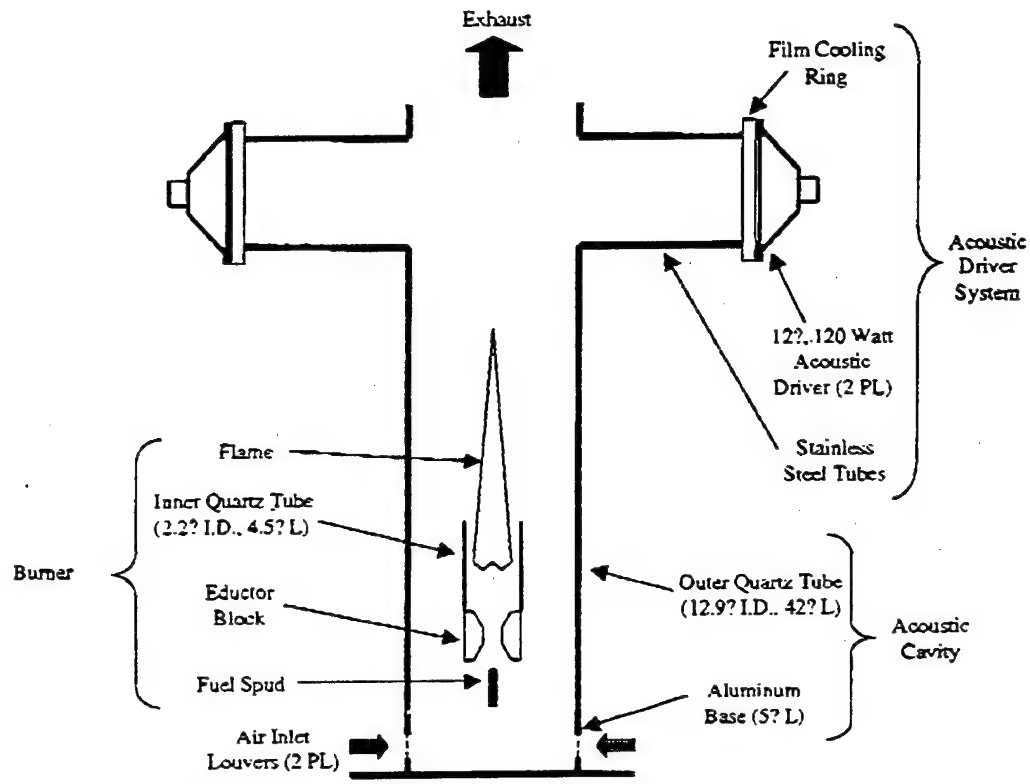


Figure 4. Spud Burner Test Section

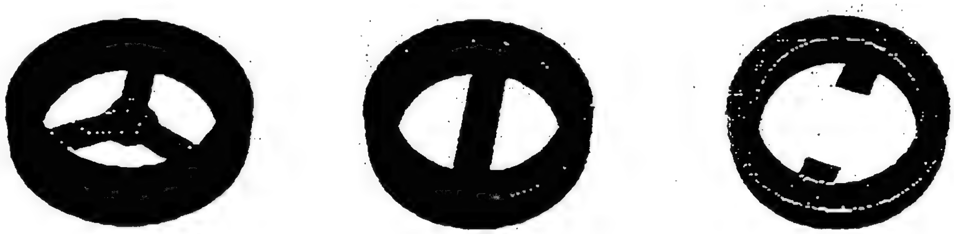
The fuel for the burner is methane that is premixed with nitrogen gas to increase the mass flow. The mixture is subsequently passed through a Meriam Model 50MJ10 Type 9 laminar flow element to measure the flow rate. It then exits the fuel spud and entrains additional atmospheric air into the stream. The fuel mixture is jet-mixed with the air in the eductor block, resulting in a flame stabilized in the inner quartz tube as shown in Figure 5. The quartz tube has two 1/8" slits cut on opposite sides, in order to allow the laser sheet to pass through and illuminate the flame. This was done to eliminate luminescence of the quartz tube caused by the laser sheet, which was interfering with the fluorescence signal.

The acoustic driving system is mounted above the outer quartz tube. It consists of a large stainless steel cross, with an inner diameter matching the large quartz tube. The exhaust section is open to the atmosphere, providing an acoustically open exit condition. The acoustic drivers are 12" subwoofers (RS Cat No. 40-1029), with a maximum power handling capability of 120 Watts, and a sensitivity of 88 dB/W/m. They are driven in parallel by an NHT SA-2 120 Watt class-G subwoofer amplifier and a Wavetek 171 function generator. The pair of acoustic drivers is sealed to a pair of air jet film cooling rings, which are in turn sealed

to the steel structure. The film cooling rings are necessary to prevent the acoustic drivers from failing due to high gas temperatures.

Figure 5. Burner section, showing a flame stabilized in the inner quartz tube with no flameholder.

Other options for the burner section include the addition of a flameholder. Additional tests will include various flameholder configurations, in an attempt to determine which arrangements may be more or less susceptible to acoustic disturbances. As seen in Figure 6, the configurations for flameholders that have already been constructed vary widely in geometry, and blockage ratios.



(a) (b) (c)

Figure 6. Constructed flameholder configurations (shown with the upstream side on top)

The acoustic cavity consists of an aluminum ring, closed at the bottom end. It has two sets of inlet louvers cut on opposing sides to allow air to flow into the tube, while providing an acoustically closed end condition. A large diameter-matched quartz tube rests in a thin register on the aluminum ring, and extends for an additional 42". Quartz was used in order to withstand high flame temperatures, as well as to allow transmission of the ultraviolet laser sheet and fluorescence signal. The tube also has several laser-drilled holes at various locations to provide instrumentation entry ports.

Test procedures involved the following steps:

1. Ignition of the burner.
2. Increase mass flow rates to test conditions.
3. Allow the laser sheet to pass through the flame.
4. Set the acoustic drivers to appropriate power level.
5. Begin data acquisition (recording pressure, temperature, ICCD camera trigger, and laser energy)
6. Start ICCD camera system.
7. Save data.

5.2 Data Processing

An extremely large amount of data was generated by these experiments. In order to process the data, several programs were written in Matlab and C to automate this task. Processing involved matching each laser shot with a camera image, and then determining when it occurred with respect to the pressure oscillation.

The pressure transducer signal was bandpass filtered, using a phase preserving 4th order Butterworth filter that was centered about the acoustic driving frequency. The images were then phase-locked in order to determine the correct phase relation (see Figure), and correlated with the filtered transducer signal.

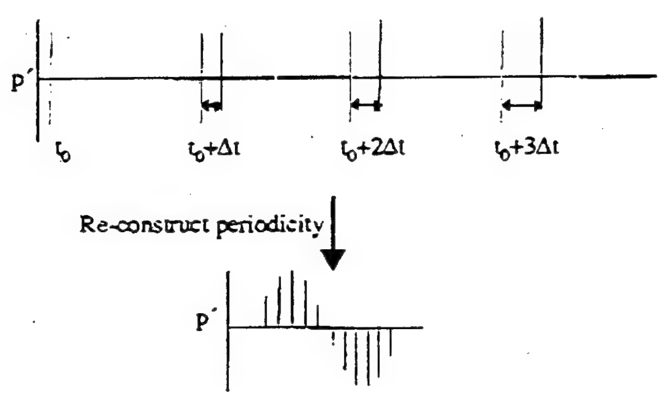


Figure 4. Phase-locking technique

The correlated images were then placed into their respective phase bins and averaged together, compensating for shot-to-shot variations in laser energy. The images were then compensated for background fluorescence.

5.3 Results

The findings of these experiments are still under analysis, although some preliminary results are presented here. The images in Figure display the fluorescence intensity of the OH PLIF signal, with red corresponding to high intensity and descending down to low intensity blue. The images are the result of 2000 images phase-locked to the filtered pressure transducer signal and correlated into 12 "bins". The flame burning zones are clearly denoted near the walls of the inner quartz tube. The image intensity is higher on the left side, since the laser sheet is travelling from left to right. The laser sheet is attenuated as OH radicals absorb it, which results in the relative fluorescence on the right being less than on the left. A horizontal banding effect can be seen in the images. This is due to the manufacturing process of the large outer quartz tube, which leaves ripples in the surface. These ripples act as lenses, and produce the banding effect observed. A discontinuity or cleft can also be seen in the lower right area of the images. This is possibly the result of laser energy entering the inner quartz tube through the second slit on the right as the sheet diverges. It could then be transmitted through the tube by total internal reflections, and emerge at the cleft location. It appears as a dark spot, since the images have been background subtracted.

The frequency of the acoustic driver was 22 Hz, with the methane and nitrogen gas flow rates being 26.1 L/min and 8.10 L/min respectively. The mean jet velocity exiting the spud is 13.1 m/s.

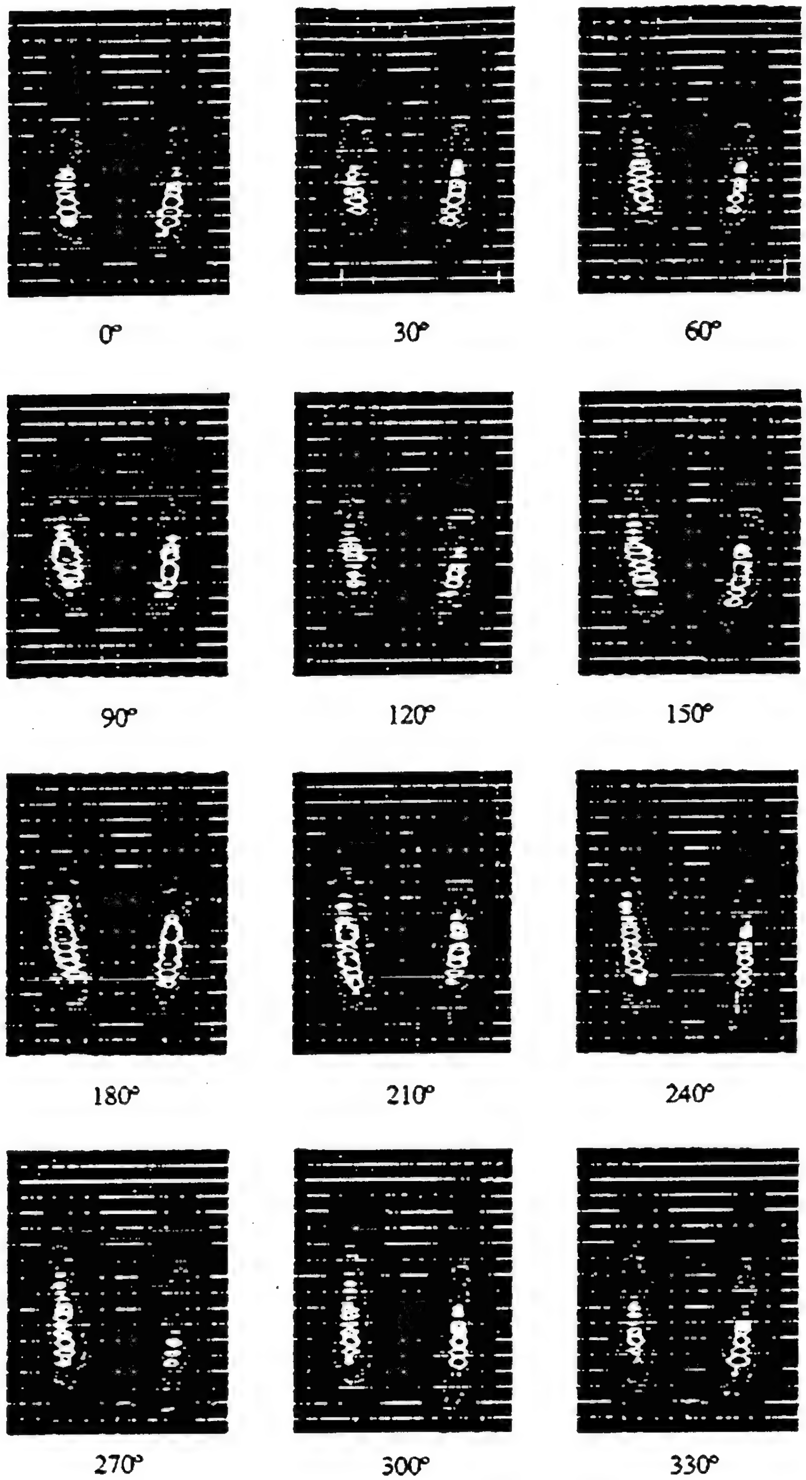


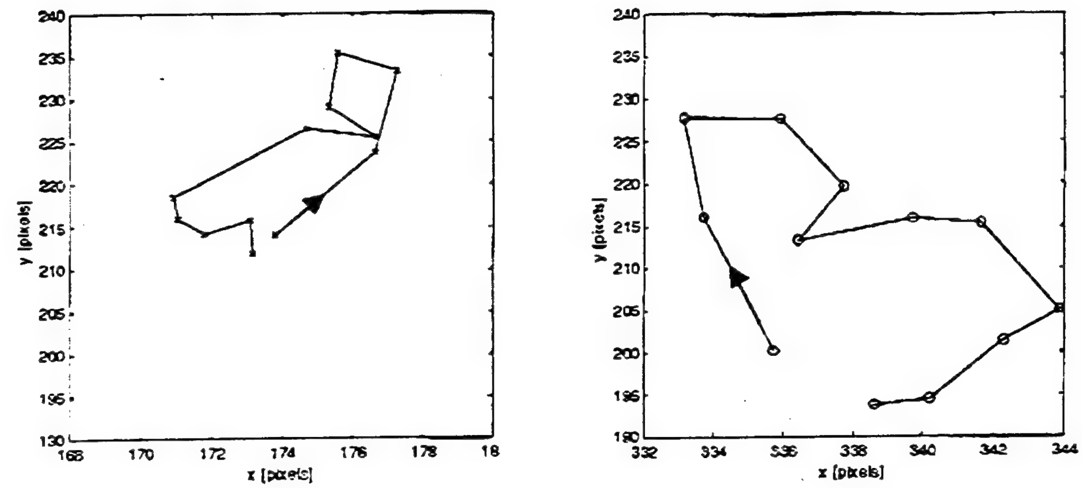
Figure 5. Phase-locked (relative to fundamental pressure mode) OH PLIF images with no flameholder.

The OH PLIF images were split into left and right halves. The "moment of intensity" was integrated over each of the halves, to locate the center of intensity. The result are plots (
Figure and Figure) without and with the flameholder respectively, of the center of concentration of the OH radical as it evolves over the phase of the fundamental pressure mode. The hydroxyl radical is focused on in this study, as it is a good marker for the heat release in the flame. The first point, just before the arrow corresponds to a pressure phase of 0°, and each subsequent point increases the phase by 30°. Both sides are plotted on the same scale, and it is evident that the right side is circulating at a higher axial position and over a wider range. This is due to an asymmetry in the inlet louvers. The right louver is approximately twice as large as the louver on the left, thus allowing more air to be entrained and providing a larger mass flow rate.

It should be noted that the maximum height of the center of intensity occurs at approximately a pressure phase of 90°, which corresponds to the maximum pressure, since a sinusoid was chosen as the pressure baseline. Also, the scale of the y-axis for the flame with no flameholder is much larger than the flame with a flameholder.

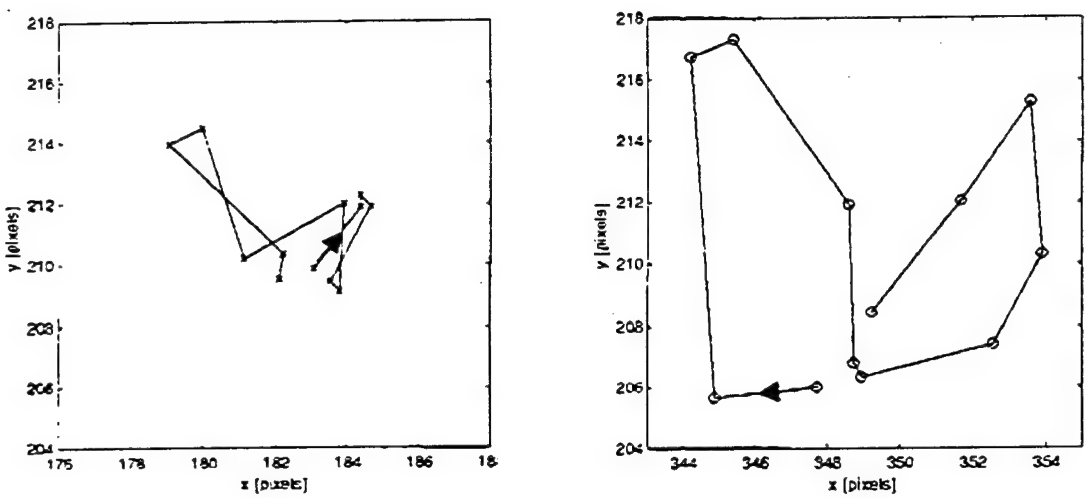
The remainder of data presented in this report is for the burner configuration with no flameholder, since it is representative of the results obtained in the study. A segment of the pressure data is presented in Figure (a). The FFT in Figure (b) clearly reveals the fundamental mode at 22 Hz. Prominent higher harmonics include the 3rd, 4th, 5th, and 7th modes. A similar set of plots is presented for the heat release in Figure . In order to generate this set of data, the number of bins for use in phase locking was increased from 12 to 36 to yield more data points. Higher resolutions than 36 bins were felt to incur too much error, due to a low number of images being averaged into some of the bins. The intensity data was computed for the entire flame in each bin, and normalized by the overall intensity average. In Figure (a), unity amplitude corresponds to the average heat release over an entire period.

Experiments were conducted at several fuel mixture flow rates and driving frequencies. The burner was operated in two configurations, with no flameholder and with the "tabs" flameholder of Figure 6(c). OH PLIF was performed on the flame that stabilized inside the inner quartz tube. The laser was tuned to excite an OH line at 281.738 nm, with approximately 52 mJ/pulse of energy. For each set of conditions, two thousand images were acquired by the ICCD camera system. Images acquired by the camera were timed to occur 30 ns before the laser pulse trigger, with a gate width of 200 ns.



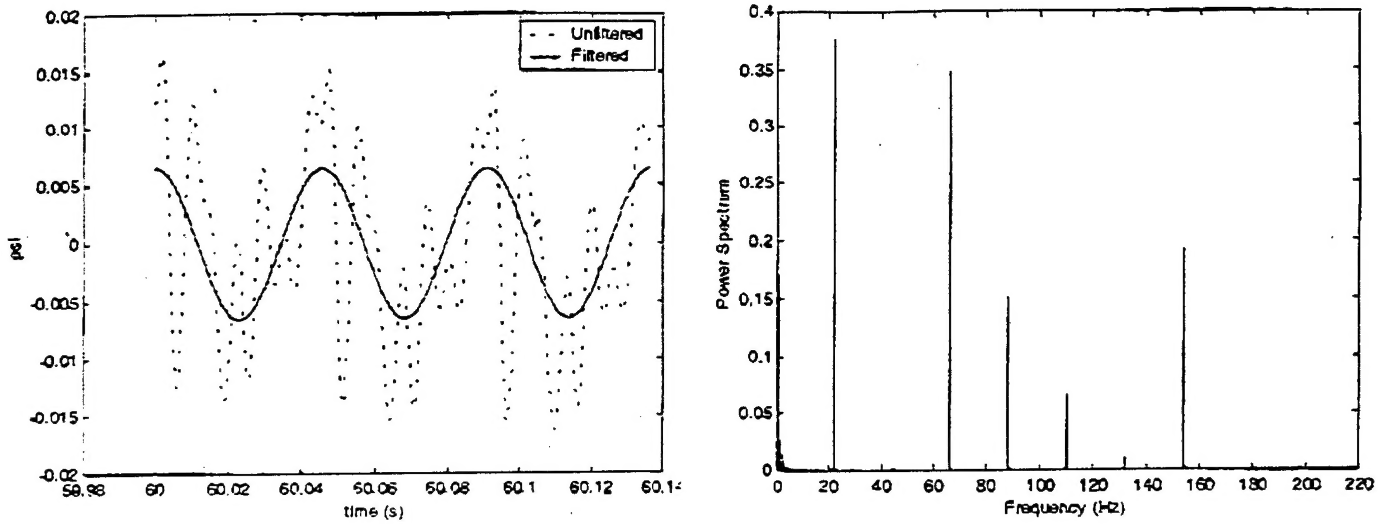
(a) (b)

Figure 6: Left (a) and Right (b) sides of the flame, tracing center of intensity of the heat release with no flameholder. Each point represents an increase in phase of 30° with respect to the fundamental pressure mode.



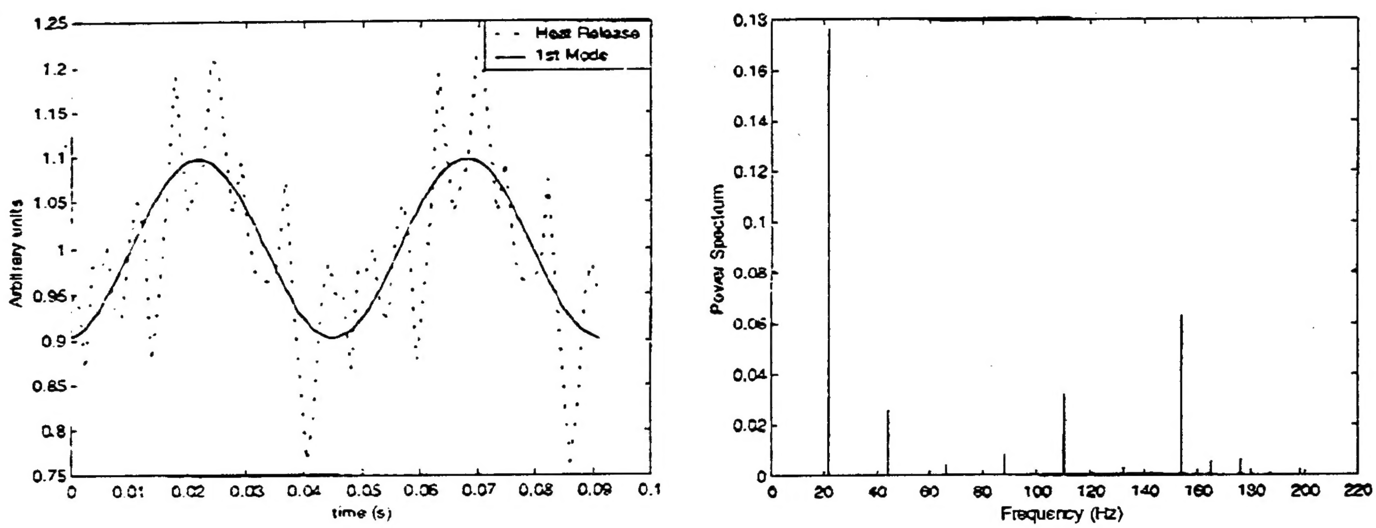
(a) (b)

Figure 7: Left (a) and Right (b) sides of the center of intensity of heat release with the "tabs" flameholder [see Figure 6 (c)]. Each point represents an increase in phase of 30° with respect to the fundamental pressure mode.



(a) (b)

Figure 8. Pressure transducer data (no flameholder): (a) unfiltered and bandpass filtered about the fundamental mode (22 Hz) (b) FFT of unfiltered signal



(a) (b)

Figure 9. Heat release (no flameholder): (a) unfiltered and filtered signals and

(b) FFT of unfiltered signal

Comparison of the FFTs for both the pressure and heat release traces in Figure (b) and Figure (b). respectively, show strong coupling between the 1st, 5th, and 7th modes. The fundamental mode is 22 Hz as expected. Figure shows the various phase relations between these modes. The pressure trace is normalized to match the heat release amplitude.

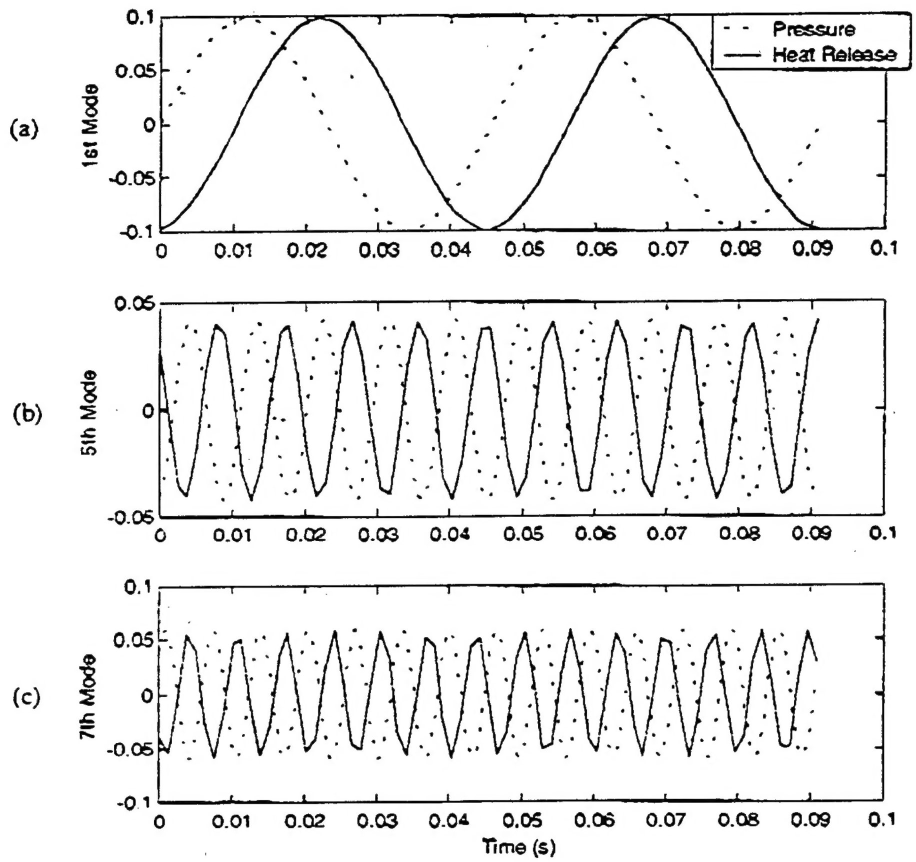


Figure 10: Phase relationships between pressure and heat release with no flameholder for the (a) 1st mode, (b) 5th mode, and (c) 7th mode.

The phase difference was computed for each mode, and displayed in Table 2.

Mode	Phase difference
1st	-81.3°
5th	-148.3°
7th	-181.8°

Table 2. Phase difference between pressure and heat release with no flameholder.

6 Preliminary Conclusions

The technique of phase-locked PLIF of the OH radical has been demonstrated to be a feasible diagnostic tool in the study of flame-acoustic interactions. The conditions tested of no flameholder and the "tabs" flameholder, show markedly different heat release characteristics, as seen by comparison of Figure and Figure . It is premature to draw any conclusions as to whether the flameholder under test enhanced or decreased the sensitivity of the flame to the acoustic field, but it is encouraging that measurable differences occurred. A wider parameter study, involving more flow conditions and burner configurations is required to quantify the effects of changes in flameholder geometry.

Application of the PLIF system is the most significant part of our effort at Caltech to develop new experimental methods for measuring the dynamical response of combustion zones. We are currently assembling an LDV system intended to operate on reflected signals (seeding the flame with small particles may be necessary). A major purpose is to measure the velocity fluctuations in flames and downstream of combustion zones, the most important applications being solid propellants. We anticipate applying LDV and PLIF measuring systems simultaneously to the same combustion system, thereby giving, the opportunity for a mutual check on the two methods. Such tests have not previously been attempted.

7 Expenditures

The following page is a detailed accounting of the expenditures of the funds. We expect that the remaining matching funds provided by Caltech will be used in the very near future to up-grade our data processing equipment.

Nd:YAG + tunable dye laser system	Continuum 9010/ND6000	$	118,400.00
Frequency mixer/doubler	Uniwave	$	19,600.00
ICCD Camera	Princeton Instr. Imax	$	34,700.00
F/2.8 UV Lens	Electrophysics Corp	$	895.00
Misc. Optics	glasses,dye,optics,cleaners	$	8,265.07
Energy Meters/Ratiometer	Molectron J50/PM30V1/EPM2000	$	7,717.25
Optical Table (4'x8'x12")	Used + breadboard	$	3,263.00
Oscilloscope	Tek 380-16SC & K212	$	4,865.50
Pentium II 400MHz PC		$	2,864.00
	Subtotal	$	200,569.82
	Tax	$	16,547.01
	Shipping	$	1,553.05
	TOTAL DURIP	$	218,669.88

Caltech Matching Funds

Item	Supplier		Cost
F/1.2 UV Lens	Roper Scientific/Princeton Instr.	$	10,000.00
Mass balance	VWR Scientific Products	$	350.00
	Subtotal	$	10,350.00
	Tax	$	853.88
	TOTAL EXPENDED MATCHING FUNDS	$	11,203.88
	TOTAL MATCHING FUNDS AVAILABLE	$	12,796.00